CHAPTER 1

Grapevines in a changing environment: a global perspective

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Abstract

Agricultural production is environmentally sensitive, being highly influenced by changes in climate, soil water and nutrition, and land use practices. From a climate perspective, agriculture is extremely vulnerable to climate change as most crop systems have been optimized to fit a given climate niche allowing for economically sustainable quality and production. These climatic niches range from fairly broad conditions suitable for crops such as wheat or corn to more narrow conditions suitable for specialty crops such as grapevines. Potential agricultural responses to changing climates reflect the interactions between temperature, water availability and timing, increasing soil salinity and nutrient stresses, and increasing carbon dioxide concentrations. As such, understanding agricultural impacts from climate change necessitates integrated information and research examining the combined effects of these and other factors. This chapter provides an overview of many of these issues through the discussion of how climate change and variability impact the structure and suitability for viticulture and wine production worldwide.

Keywords: climate, wine, viticulture, grapevines, phenology

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List of abbreviations

CO ₂	Carbon dioxide
°C	Degrees Celsius
ENSO	El Niño Southern Oscillation
IPCC	Intergovernmental Panel on Climate Change
mm	Millimeter
$T_{\rm max}$	Maximum temperature
T_{\min}	Minumum temperature

1.1 Introduction

Human interactions within Earth's environment have brought significant changes, producing a situation in which we now face some of the most complex collection of ecological problems in our history. Driven by population growth and often ecologically unsustainable processes these problems include an increasingly less predictable and stable climate and a wide range of interrelated social, environmental, and economic problems. Compounded by growing water scarcity, deforestation, species extinction, and ocean acidification, our ability to function as a species is challenged more than ever before (IPCC, 2013). Climate is at the forefront of these issues as it presents a very complex, highly variable, and pervasive factor in our natural Earth and human-based systems. From controlling vegetation patterns and geological weathering characteristics to influencing water resources and agricultural productivity, climate is at the heart of the delicate equilibrium that exists on Earth. While it is clear from historical evidence that changing climates are a part of the Earth's natural adjustments to both internal and external forces (e.g., volcanic eruptions and solar variability), more and more evidence is pointing to increasing human impacts on our climate (IPCC, 2013). Processes such as desertification, deforestation, and urbanization, by which the global energy balance is disrupted, and changes in atmospheric composition that enhance the greenhouse effect beyond its natural equilibrium demonstrate that our role in changing the climate is increasing.

Agriculture represents probably one of the most complex aspects of humanenvironment interactions whereby we need increasingly more productive systems to feed our growing population, yet aspects of doing so will, and will likely continue to, exacerbate the problems. As such, agriculture has both a role in producing some of our challenges, but more importantly has been increasingly asked to develop sustainable practices that reduce our vulnerability and increase our adaptive capacity in the face of global change (Diffenbaugh et al., 2011). Today, as in the past, climate is clearly one of the most important factors in the success of all agricultural systems, influencing whether a crop is suitable to a given region, largely controlling crop production and quality, and ultimately driving economic sustainability (Jones et al., 2012). While decisions about what crop to grow commercially are largely driven by regional history and tradition, they are also influenced by regional to international economics. However, both tradition and economics are ultimately driven by the ability to grow the crop sustainably within a given climate (White et al., 2009). From broadacre crops such as wheat, rice, corn, and soybeans to specialty crops such as fruits and vegetables, tree nuts, dried fruits, and coffee, they all have strong ties to global to regional climates. While broadacre crops are clearly more important as global food sources, specialty crops present unique sensitivities to climate that have made them especially interesting to researchers examining global change. This fact is never more evident than with viticulture and wine production where climate is arguably the most critical environmental aspect in ripening fruit to its optimum quality to produce a desired wine style (Jones, 2014).

The complex influences that result in wine are often embodied in the concept of 'terroir', a term that attempts to capture all of the environmental and cultural influences in growing grapes and making wine (Vaudour, 2002; White et al., 2009; Tomasi et al., 2013). Terroir is derived from the Latin 'terre' or 'territoire' and its first modern definition appears as 'a stretch of land limited by its agricultural capacity'. Historically, the use of terroir as defining aspects of landscapes grew out of the traditions of the Cistercian monks in Burgundy (wine origin), but the term was also broadly embraced by the French as an agricultural production concept tied to specific regions (i.e., wine, cheese, pâté, and other specialty crops) (White et al., 2009). While definitions and influences associated with terroir continue to be debated (Vaudour, 2002; Jones, 2014), what is important is the complexity of environmental influences that the concept encompasses (Tomasi et al., 2013). At the broadest definition, climate produces the most easily identifiable differences in terroir through its influence on vine growth, fruit ripening, and wine styles (van Leeuwen et al., 2004). Varieties that are best suited to a cool climate tend to produce wines that are more subtle with lower alcohol, crisp acidity, have a lighter body, and typically bright fruit flavors, while those from hot climates tend to be bolder wines with higher alcohol, lower acidity, a fuller body, and more dark or lush fruit flavors. Geology, soil, and landscape all interact with climate and the variety to produce the subtle differences and/or expression of aromas, flavors, and styles within the same climate or region (van Leeuwen et al., 2004; Jones, 2014). Finally, through their decisions about what to grow, where, and how, humans can accentuate or camouflage terroir (Bohmrich, 2006). Both as a general interest and as the result of numerous impacts from global environmental changes, science has been asked to help identify and define the myriad interrelated aspects of terroir that together influence viticulture and wine production worldwide.

1.2 Climate suitability for viticulture and wine production

As in the past, today's wine production occurs over relatively narrow geographical and climatic ranges. Winegrapes also have relatively large cultivar differences in climate suitability, further limiting some winegrapes to even smaller areas that are climatically appropriate for their cultivation (Jones, 2006). These narrow niches for optimum quality and production put the cultivation of winegrapes at greater risk from both short-term climate variability and long-term climate changes than other more broadacre crops. While historically associated with Mediterranean climates, viticulture has spread throughout much of the world, with vineyards found as far north as in Scandinavia (helped by a warming climate), on east coasts of continents (e.g., China, Japan, and the eastern United States) and near the equator, where two crops per year are produced (e.g., Brazil). In these regions additional weather/climate risks of winter freezes, untimely rainfall, tropical cyclones, or increased disease risk pose challenges, but innovation and intent has developed thriving local to regional wine identities (Jones et al., 2012). The broader bounds for viticulture and wine production occur in climates where growing season temperatures average 13–21 °C (Figure 1.1). The climate-maturity zoning in Figure 1.1 was developed based upon both climate and plant growth for many cultivars grown in cool to hot regions throughout the world's benchmark areas for those winegrapes (Jones, 2006). While many of these cultivars are grown and produce wines outside of their individual bounds depicted in Figure 1.1, these are more bulk wine (high yielding) for the lower end of the market and do not typically attain the typicity or quality for those same cultivars in their ideal climate. Furthermore, growing season average temperatures below 13 °C are typically limited to hybrids or very early ripening cultivars that do not necessarily have largescale commercial appeal. At the upper limits of climate, some production can also be found with growing season average temperatures from 21 to 24 °C, although it is mostly limited to fortified wines, table grapes and raisins.

Over the 13–21 °C range of growing season average temperatures that most viticulture and wine production occur, individual cultivars can be found in fairly narrow climate zones (Jones, 2006). For example, Pinot Noir has one of the narrower climate suitability zones, being grown mostly in cool climates with growing seasons that range from roughly 14 to 16 °C in places such as Burgundy or the Willamette Valley of Oregon. Across this 2 °C climate niche, Pinot Noir produces the variations in style for which is it known, with the cooler zones producing lighter, elegant wines and the warmer zones producing more full-bodied, fruit-driven wines. While Pinot Noir can be found outside these climate bounds, it is typically unripe or overripe and readily loses its typicity. For a warmer climate cultivar such as Cabernet Sauvignon, the climate suitability zone in growing season average temperatures is wider (16–20 °C), spanning from intermediate to hot climates in regions from Hawke's Bay, New Zealand, to Bordeaux and Napa.



intermediate, warm, and hot growing season temperatures requiring cultivars (Jones, 2006). Note that grapevines are not necessarily grown across all October-April in the Southern Hemisphere) derived from the WorldClim database (Hijmans et al., 2005). The classes depict the climate types for cool, Figure 1.1 General climate zones for viticulture defined by growing season average temperatures (April–October in the Northern Hemisphere and areas depicted, as other climate issues could be limiting to viticulture.

1.3 Climate change and variability

Recent research on aspects of global environmental change on viticulture and wine production reveal significant changes and many unknowns (Fraga et al., 2012). From a general climate perspective, wine regions worldwide have seen changes in average climate structure producing warmer and longer growing and dormant periods (Jones et al., 2005a). Growing season temperatures in many of the best wine- producing regions in the world warmed 1.3 °C on average during 1950–2000. However, the warming was not uniform across all regions with greater magnitudes in the western United States and Europe and less warming in Chile, South Africa, and Australia. Also trends between day and night temperatures vary by region, with some seeing much more significant warming at night and others seeing more heat stress events through higher daytime temperatures (Nemani et al., 2001; Jones et al., 2005b). More regionally specific and temporally resolved research concur with the global observations of wine region temperature trends (Jones and Davis, 2000; Jones, 2005; Webb et al., 2008; Ramos et al., 2008; Hall and Jones, 2009; Urhausen et al., 2011; Bock et al., 2011; Koufos et al., 2013; and others). In addition to warmer growing seasons with greater heat accumulation, many of the world's wine regions have experienced a decline in frost frequency and shifts in the timing of frosts (Jones, 2005; Donat et al., 2013; Molitor et al., 2014). A comprehensive global assessment of 27 core indices that define the frequency or severity of extreme of temperature and precipitation events (Peterson, 2005) was conducted over 1951-2011 worldwide (Donat et al., 2013). The results show that minimum temperature extremes have been warming at 2–4 times the rate of maximum extremes, resulting in a decline in the diurnal temperature range. Likewise, the percentage of days with temperatures in the lower 10th percentile has declined while the percentage in the upper 90th percentile has increased. During this period the length of the growing season has increased, while frost days (<0 °C) and cold spells (consecutive cold days) have declined and warm nights (T_{min} > 20 °C), warm days (T_{max} > 25 °C), and warm spells (consecutive warm days) have increased. However, cold extremes still occur and there is some evidence that acclimation to more benign conditions can make both the plant system and human readiness for such events more susceptible to their occurrence (Gu et al., 2008). For precipitation, the annual contribution from very and extremely wet days (>95th and 99th percentile) has increased significantly while the number of consecutive dry days (<1 mm) has declined globally (Donat et al., 2013).

Depending on the underlying emission scenario, climate models predict continued increases in global temperature of 1.3–4.8 °C by the end of this century (IPCC, 2013). Furthermore, observations and modelling have shown that changes in climate have not and are not likely to be manifested in just changes in the mean, but also in the variance where there are likely to be more extreme heat occurrences but still swings to extremely cold conditions (IPCC, 2013). Therefore, even if the average climate structure gets better or more suitable in some regions, variability will still be very evident and possibly even more limiting than what is observed today (Schär et al., 2004). Work over the last three decades using model projections show that the observed warming trends in wine regions worldwide are predicted to continue. Globally, Jones et al. (2005a) found that mean growing season temperatures could warm by an average 2 °C in 27 of the world's top wine-producing regions by 2049. Numerous studies have examined changes across Europe and point to similar trends with increases in temperatures and spatially variable changes in precipitation (Stock et al., 2005; Fraga et al., 2012). Specifically in Spain, Rodriguez et al. (2005) examine different emission scenarios to place lower and upper bounds on temperature and precipitation changes and find increasing temperature trends of 0.4–0.7 °C per decade with summer warming greater than in the winter. Overall the changes result in warming by 2100 of between 5 and 7 °C inland and 3 and 5 °C along the coast. Concomitant with these temperature projections, Rodriguez et al. (2005) show much drier springs and summers and lower annual rainfall, which was shown to be less spatially homogeneous across Spain than is temperature. Furthermore, to examine grapevine responses to climate change, Lebon (2002) used model output to show that the start of Syrah ripening (véraison) in Southern France would shift from the second week of August today to the third week of July with a 2 °C warming and to the first week of July with a 4 °C warming. In addition, spatial modeling of suitable zones for viticulture in Europe show latitudinal, coastal, and elevation shifts from historic wine regions (Malheiro et al., 2012; Santos et al., 2012; Moriondo et al., 2013). Similar results have been found elsewhere, with White et al. (2006) estimating that the potential premium winegrape production area in the conterminous United States could decline by up to 81 percent by the late twenty-first century due to changes in temperature, especially heat extremes. In another regional analysis for the west coast of the United States examining yields of perennial crops in California, Lobell et al. (2006) found a range of warming across climate models of ~1.0-3.0 °C for 2050 and 2.0-6.0 °C for 2100 and a range of changes in precipitation from -40 to +40 percent for both 2050 and 2100. In Australia, Webb et al. (2007) analyzed climate change scenarios for viticulture showing that temperatures by 2070 are projected to rise in Australia by 1.0–6.0 °C, increasing the number of hot days and decreasing frost risk, while precipitation changes are more variable but result in greater growing season stress on irrigation. Hall and Jones (2009), modelling growing season climates for Australia, found that eight of the 61 recognized wine regions in the country would be warmer than the known growing season temperature threshold for suitability by 2030, 12 by 2050 and 21 by 2070 without further adaptive measures. In South Africa, regional projections of rising temperatures and decreased precipitation have been shown to put additional pressure on both the phenological development of the vines and on the necessary water resources for irrigation and production (Carter, 2006).

While the average climate structure in a region determines the broad suitability of winegrape cultivars, climate variability influences issues of production and quality risk associated with how equitable the climate is year in and year out (Jones et al., 2012). Climate variability in wine regions influences grape and wine production through cold temperature extremes during the winter in some regions, frost frequency and severity during the spring and fall, high temperature events during the summer, extreme rain or hail events, and broad spatial and temporal drought conditions. Climate variability mechanisms that influence wine regions are tied to large-scale atmospheric and oceanic interactions that operate at different spatial and temporal scales over most of the globe. The most prominent of these is the large-scale Pacific sector El Niño-Southern Oscillation (ENSO), which has broad influences on wine region climates from North America (Jones and Goodrich, 2008), Australia and New Zealand (Gordon, 1986; Power et al., 1999), South Africa (Tyson, 1986), South America (Garreaud et al., 2009), and Europe (Rodó and Comín, 2000). However, the effects of ENSO on wine region climate variability varies tremendously in magnitude and is of opposite sign depending on the location of the wine region and is often coupled with other more influential regional mechanisms (Jones and Goodrich, 2008). There is also some evidence that these broad climate variability mechanisms are likely to become more variable in the future, potentially bringing greater extremes worldwide (Trenberth and Fasullo, 2013).

1.4 Environmental impacts on viticulture and wine production

Numerous impacts associated with plant growth, fruit characteristics, and pest and disease issues have been seen in wine regions and are likely to continue in the future (Bission et al., 2002). For Europe in general, grapevine phenological timing has showed strong relationships with the observed warming, with trends ranging from 6 to 25 days earlier over numerous cultivars and locations (Jones et al., 2005b; Duchêne and Schneider, 2005; Bock et al., 2011; Tomasi et al., 2011; Urhausen et al., 2011; Koufos et al., 2013). Furthermore, from the limited data available in Australia and across the United States, observed changes in grapevine phenology have ranged 2-5 days earlier per decade over the last 25–35 years depending on cultivar and region (Wolfe et al., 2005; Webb et al., 2011; Jones, 2013) and are strongly correlated to warmer springs and summers. Changes are greatest for véraison and harvest dates, which typically show a stronger, integrated effect of a warmer growing season. Interval lengths between the main phenological events have also declined, with bud break to bloom, véraison, or harvest dates shortening by 14, 15, and 17 days, respectively (Jones et al., 2005b; Tomasi et al., 2011). A meta-analysis over all locations globally and cultivars shows that grapevine phenology has been responding by 3–6 days per 1 °C of warming over the last 30–50 years.

With earlier and more rapid plant growth the potential for changes to ripening profiles and wine styles is evident (Petrie and Sadras, 2008). In a warmer than ideal environment for a given cultivar, the grapevine goes through its phenological events more rapidly, resulting in earlier and likely higher sugar ripeness, and, while the grower or winemaker is waiting for flavors to develop, the acidity is lost through respiration, resulting in unbalanced wines without greater afterharvest inputs or adjustments in the winery (Vierra, 2004). As a result of warming conditions to date, combined with other complex consumer and economic issues, higher alcohol levels have been observed in many regions (Jones, 2010). For example, research has found that potential alcohol levels of Riesling at harvest in Alsace have increased by 2.5 percent (by volume) over the last 30 years and was highly correlated to significantly warmer ripening periods and earlier phenology (Duchêne and Schneider, 2005). In Franconia (Bock et al., 2011), the Rhine Valley (Schultz and Jones, 2010), the Loire Valley (Neethling et al., 2012), and Slovenia (Vrsic et al., 2014), research has also found that as sugar levels rose, acidity levels declined and that both were significantly correlated with increases in temperatures. Godden and Gishen (2005) summarize trends in composition for Australian wines showing increases in the alcohol content of 12.3 to 13.9 percent for red wines and 12.2 to 13.2 percent for white wines from 1984 to 2004. Also for Napa Valley, average alcohol levels rose from 12.5 to 14.8 percent from 1971 to 2001 while acid levels fell and the pH climbed (Vierra, 2004). Orduña (2010) argues that wine-making regions with increases in extremely hot temperatures will see inhibited vine metabolism, leading to reduced metabolite accumulations and a significant increase in the risk of color and aroma degradation (Mori et al., 2007) along with higher instances of wine spoilage. Furthermore, harvests that occur earlier in the summer, in a warmer part of the growing season (e.g., August or September instead of October in the Northern Hemisphere), will result in hotter fruit being harvested (which readily loses flavor and aroma compounds) with the potential for greater fruit desiccation, without greater irrigation inputs (Webb et al., 2011).

Much work has been done examining the likely impacts of climate change on the growth and yield of numerous agricultural plants worldwide through experiments and modeling (e.g., Challinor et al., 2014, and others cited therein). Yet, knowledge about climate change effects on diseases, pests and weed development, and related plant responses is still lacking, and thus insufficiently implemented within crop models (Chakraborty et al., 1998). In particular, plant pathogens may be especially responsive to global change, given their both short generation times and effective dispersal mechanisms (Coakley et al., 1999). Furthermore, because of altered temperature and precipitation regimes with climate change, growth stages and/or rates of development in the life cycle and pathogenicity of pathogens may be altered as well, while modification of the physiology and resistance of host plants is also likely to occur (Chakraborty et al., 1998). There is even more limited systematic research on the consequences of changing temperature and precipitation on grapevine pests and diseases (e.g., Chakraborty et al., 1998; Salinari et al., 2006; Walton et al., 2010) although various observations indicate that significant alterations are going on already. From the limited experience in viticulture regions it is likely that pest and disease pressure will increase and also shift to new areas further toward the poles with warmer winters and warmer night temperatures. Cool climate viticulture zones most probably will face more damage by berry rots, higher population densities, or more generations of pest insects and mites and an increasing significance of current secondary pests in the future, but the effects are likely to differ among pest species depending on the specific modes of interaction. For example, Pierce's disease has been predicted to move into Oregon and Washington wine regions where it is currently not present due to lower winter temperatures (Tate, 2001). Walton et al. (2010) found that mite-related short shoot syndrome in Oregon is driven by population dynamics controlled by climate and that mites begin feeding at the onset of shoot growth when tissue is most susceptible in spring. Changes in climate have likely synchronized this timing more in some regions and will alter the timing further in the future. In Italy, Salinari et al. (2006) modeled the occurrence of downy mildew and predicted that disease pressure would increase in the future due to increasing temperatures. In Great Britain, modeling of virus-vector nematodes showed that they are predicted to spread at a rate of 160–200 km per 1 °C but would also be aided by humans and could spread even faster (Neilson and Boag, 1996). While there has been no direct climate change assessment on one of the biggest pests for viticulture, phylloxera, there is a likely increasing risk of spread based on the increased rate of emergence of the insect from the soil with warming (Benheim et al., 2012). Increasing drought risk with climate change might also add to phylloxera impacts because, after a drought event or when water allocation to vines is reduced, phylloxera population abundance increases, as does greater plant stress and a more rapid decline in plant health.

Beyond pest interactions, soil also strongly influences yield and quality in wine production. Soil erosion, degradation, and salinity are likely to be major indirect effects of climate change on viticulture and wine production (Anderson et al., 2008). Climate change is expected to lead to a more vigorous hydrological cycle, including more total rainfall and more frequent high-intensity rainfall events (IPCC, 2013). Observations show that rainfall amounts and intensities increased on average globally during the twentieth century (Donat et al., 2013), and according to climate change models they are expected to continue to increase during the twentyfirst century (IPCC, 2013). These rainfall changes, along with expected changes in temperature, solar radiation, and atmospheric CO_2 concentrations, will likely have significant impacts on soil erosion rates (Nearing et al., 2004). Even in cases where annual rainfall is projected to decrease, system feedbacks related to decreased biomass production could lead to greater susceptibility for soil erosion. There will likely be nonlinear effects of climate change caused by interactions between soil, climate, and nutrition, in part dependent on

adaptation in vine management where responses could potentially exacerbate, or ameliorate, the potential changes in erosion rates (Anderson et al., 2008; Hayman et al., 2009). For example, research examining climate change influences on soil erosion and nutrition loss in steep slope vinevards in Slovenia suggested that periodic soil tillage during the growing season could limit the impacts if done at the right time (Vrsic et al., 2011). However, it was stressed that the seasonality of extreme rainfall events might change in the future, resulting in challenges to developing an adaptive plan of periodic soil tillage. In regions with very arid climates there is often a decline in soil structure and increased salinity (Clark et al., 2002; Richards et al., 2008). Soil structure decline and increased sodicity can occur when saline water is used for summer irrigation and then subsequently the soil receives high-quality rainwater during winter (Clark et al., 2002). Decreased flows in arid regions in the western United States and Australia is likely to result in increased salinity of irrigation water in many viticulture regions. Furthermore, a changing climate and other demands on water will increase the pressure to restrict irrigation, ultimately increasing rootzone salinity with greater impacts on wine quality over time.

The projected changes in atmospheric parameters are of key importance for many agricultural processes and practices, but especially important for photosynthetic activity and biomass accumulation are atmospheric levels of CO₂. While atmospheric CO, concentrations have fluctuated over Earth's history, they have increased substantially since industrialization and are predicted to continue to rise in the future (IPCC, 2013). For perennial crops (such as vineyards), Lobell et al. (2006) state that under future climate change actual yield changes will reflect the combined influence of climatic factors and the potentially positive effects of management, technology, and increased atmospheric CO₂. While research on CO₂ effects on grapevines and wine are limited temporally, spatially, and across numerous varieties, there is some evidence of likely increases in leaf area and vegetative dry weight from increased atmospheric CO₂, while interannual variation in yield is likely to increase (Bindi et al., 1996). Subsequent studies by Bindi et al. (2001a, 2001b) found that acid and sugar levels in the grapes during their growth period were equally increased under elevated atmospheric CO, concentrations. However, at maturity no differences were found for acid, sugar or other wine quality variables and, while there was a trend towards higher concentrations of red wine pigments in enriched CO, treatments, the authors indicated that it could have been due to vinification effects (Bindi et al., 2001a, 2001b). It was concluded that the effect of higher CO, concentrations on grape and wine quality was limited and that yield increasing effects may be reduced or cancelled by the effect of warmer temperatures (Bindi et al., 2001a). It is also believed that raised atmospheric CO, is likely to result in partial stomatal closure, which indirectly leads to increased leaf temperatures, resulting in a negative feedback on photosynthetic potential (Schultz, 2000). Moutinho-Pereira et al. (2009) found that raised atmospheric carbon dioxide decreased the stomatal

density of some grapevine varieties, but that the net CO₂ assimilation rate was significantly increased, whereas stomatal conductance was reduced in elevated CO₂, leading to improvements in intrinsic water use efficiency. Work by Gonçalves et al. (2009) examining impacts on the variety Touriga Nacional found that higher CO₂ levels produce small to no differences in grape maturity variables or wine aroma compounds, but fermentation factors may influence these results. While we understand some of the issues surrounding CO₂ impacts on growing grapes and wine production, Keller (2010) brings up the important point that, in spite of the obvious importance for the global wine industry, we do not know how rising CO₂ influences temperature variations and water supply issues as they relate to vine growth, phenological timing and phase lengths, yield formation, fruit ripening and composition, and, most importantly, wine quality. Rightfully so, Keller (2010) advocates for more longer-term studies of increasing CO, so that appropriate adaptation and mitigation strategies can be developed in response to a changing climate. Furthermore, understanding the interactions of elevated CO, concentrations with changes in climatic parameters, including temperatures, extremes, soil water availability, pests, diseases, and physiological interactions remain a key aspect for assessing climate change impacts on all forms of agriculture in the future (Tubiello and Fischer, 2007; Schultz and Stoll, 2010).

1.5 Conclusions

Even with the large number of uncertainties associated with climate change, continuing research efforts are needed to help better understand numerous issues that growers are currently experiencing and are likely to see in the future (Jones and Webb, 2010; Schultz and Jones, 2010). These include (1) how crop suitability, establishment, growth, and maturity will be altered in the future, (2) whether there will be sufficient heat accumulation and precipitation to meet crop needs in the future, and (3) whether there will be sufficient regularity in climate from year to year so as to allow security of production or whether agroclimatic variability will be greater than what is environmentally/economically feasible and/or sustainable. General areas of study to address some of these issues include better understanding of the cultivar limits to climate conditions, differential vineyard management strategies, further wine-making refinements, developments in soil-rootstock compatibility, and continued plant breeding and genetic research. For cultivar suitability we clearly need a better understanding of temperature limits for viticulture, especially at the warmer end of the growth spectrum for winegrapes (Schultz and Jones, 2010). Vineyard management adaptations are numerous, including changes in row orientation, spacing, canopy management, and irrigation management that help manage heat and/or drought stresses (Keller, 2010; Webb et al., 2010). Likewise, wine-making adjustments are many and include the potential use of different yeasts that ferment to lower alcohol levels while maintaining typical flavor and aroma profiles (Contrerasa et al., 2014). The industry would benefit greatly from continued developments to more healthy plant material with less virus and lowered disease susceptibility, which would reduce the vulnerability of the plant system to environmental stresses such as climate change. Furthermore, grape-vines have a large genetic diversity (This et al., 2006) and increased understanding of the available genetic material and the maintenance of the natural biodiversity is important for being able to better adapt to climate change (White et al., 2006; Duchêne et al., 2012; Tello et al., 2012).

The remaining chapters in this book examine many of the issues detailed above and more. Several chapters examine physiological responses of grapevines to various environmental stressors that are either directly or indirectly related to climate change. Many of these issues are tied to drought, water management in vineyards (see also Chapter 3), increasing salinity (Chapter 12), and how rootstocks respond to various water and nutrient stresses (Chapter 4). Still other chapters provide additional information on the changing carbon balance in grapevines (Chapter 5), the use of remote sensing and other geospatial tools to monitor vineyard stress (Chapter 8), and information on the genetics of stress tolerance (Chapter 15).

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